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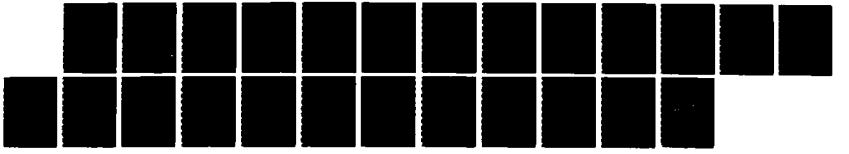

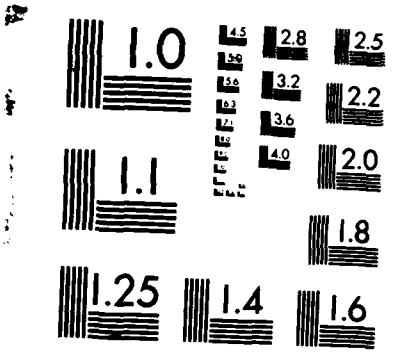


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# TRANSIT AND GPS - A REPORT ON GEODETIC POSITIONING ACTIVITIES

Patrick J. Fell

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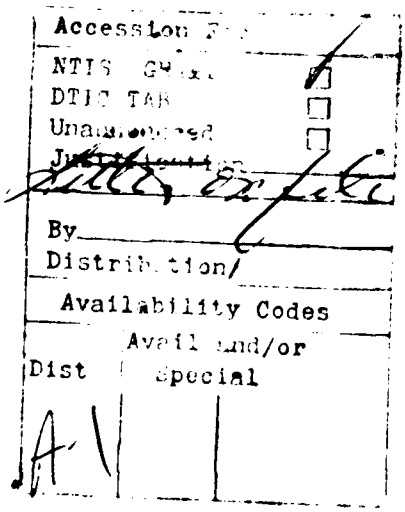

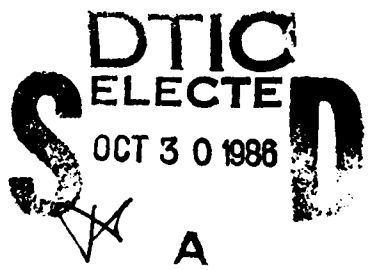


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# TRANSIT AND GPS - A REPORT ON GEODETIC POSITIONING ACTIVITIES

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## ABSTRACT

The Fourth International Geodetic Symposium on Satellite Positioning was held in Austin, Texas from 28 April to 2 May 1986. The symposium was organized as a forum for the discussion of recent geodetic activities related to precise positioning using observations from the Navy Navigation Satellite System (Transit) and the NAVSTAR Global Positioning System (GPS). In addition, the symposium promoted an exchange of ideas on the future direction of GPS geodetic activities and provided a summary of the status, policy, and plans for both the GPS and Transit systems. This report summarizes the proceedings of the meeting.

## 1. Introduction

The transition of geodetic surveying from Transit to GPS began recently with the development of portable receiver systems and the successful (for its accuracy and economy) determination of baselines. The results obtained from testing GPS for its geodetic utility have certainly met expectations from initial studies published by Fell (1980) and Remondi (1984). However, a full implementation of GPS into survey practice may be contingent upon the resolution of several issues and the completion of critical GPS program milestones. Among these are further deployment of satellites providing measurement availability and a final policy on the

civilian use of GPS. The availability and distribution of precise ephemerides to support survey data reduction remain an additional point. Yet despite these uncertainties remarkable progress has been achieved over a relatively short period. A contributing factor to this has been the development of commercial receiver systems, developed earlier with GPS than with the Transit program.

## 2. TRANSIT AND GPS - STATUS, POLICY, AND PLANS

The first session of the symposium was dedicated to presenting the status of each satellite system, future plans, and, in the case of GPS, a statement on current policy for civilian use.

The Transit system, operational since 1968, consists of three OSCAR satellites, two on-orbit spares, and NOVA satellites I and III. In terms of continued Transit availability, Sentman stated that the Navy will continue to manage the system through 1994 when it will be phased out in favor of GPS. Until that time, the probability of an operational three-plane constellation will exceed 99 percent, as the launch of available spares maintains system performance.

The development of GPS is continuing with the program nearing the end of full scale engineering development designed to verify the operational effectiveness of the GPS concept for both military and civilian users. Currently there are seven research and development Block I navigational satellites in the constellation operating on stable atomic frequency standards and providing reliable information. These satellites are orbiting in two planes separated in longitude by 120 degrees and with inclinations of 63 degrees. The operational Block II constellation of 18 satellites will be uniformly spaced in six orbital planes inclined at 55 degrees. Three

on-orbit active spares will complement the system. All satellites will be routinely tracked by five Air Force monitor stations whose observations are processed at the Master Control Station in Colorado to support navigation.

The operational GPS will provide two distinct navigation services, the Precise Positioning Service (PPS) and the Standard Positioning Service (SPS). The SPS users will have access to only the C/A code on the $L_1$ frequency of 1575.42 MHz. According to Stein, navigational accuracies from these positioning services are, respectively, 16.0 and 76.3 meters spherical error probable.

Addressing policy on the civilian use of GPS, Baker stated that the SPS was designed for civil navigation and that no direct user charges would be assessed for that service. If possible, limited civil use of the PPS would be provided. A proposed approach toward making PPS available for civil applications has been formulated and will be circulated in the civil sector for review and comment prior to any implementation action.

## 3. REFERENCE FRAMES

Decker and White provide summaries of the World Geodetic System 1984 (WGS 84), covering its development and evaluation. The WGS 84 is a general geodetic solution developed from various terrestrial and satellite data sets including Doppler and laser, geoid undulations from satellite altimetry, and mean free-air gravity anomolies. The gravity field is complete through degree and order 180 with satellite observations contributing to coefficients through degree and order 41. The reference frame differs from the Doppler 9Z-2 system by a Z-axis shift of 4.5 meters, a scale change of -0.6 ppm and a longitude rotation of 0.814 seconds. The reference ellipsoid is consistent with the defining parameters of the International

Geodetic Reference System 1980. The longitude rotation implies that WGS 84 and the North American Datum 1983 will have consistent orientation. In addition, approximately 80 datum transformations to WGS 84 have been developed using Doppler control. A question requiring further investigation is the consistency between point positions determined using WGS 84 and those obtained from 9Z-2 (or WGS 72) by direct transformation.

In other areas related to reference frames, McCarthy discussed the prediction of polar motion and UT1-UTC, concluding that 30 centimeters and 7 centimeters per day to 40 days can be achieved. Bangert presented results on the same topic and Wooden summarized Doppler polar motion results obtained during the MERIT Campaign. Of interest is the apparent improvement in Nova satellite pole position agreement with BIH after the introduction of WGS 84. Finally, the paper by Welsch addressed the problem of combining terrestrial and satellite control networks.

## 4. ORBIT DETERMINATION

Presentations on precision orbit determination for Transit and GPS concerned themselves with two approaches using terrestrial tracking data and a method for dynamically positioning lower altitude satellites from simultaneous satellite and terrestrial tracking of GPS. Procedures for orbit determination using terrestrial tracking consisted of traditional long arc reduction supported by a global network, and by regional networks. In the case where some portion of a regional network is known with high internal consistency and is used to simultaneously estimate GPS orbits and new geodetic baselines, this approach is termed the fiducial network concept. Assessments of accuracy for orbit determinations were accomplished by several methods including direct comparison of ephemerides

estimated using different data or processing conditions, examination of formal standard errors, and the comparison of simultaneously determined baselines with independent control.

For Transit satellites, one and two day orbit determinations are produced and distributed by the Defense Mapping Agency. A comparison of overlap regions of consecutive orbit determinations by Murphy provided a consistency for 1985 precise ephemerides in the range of 1 to 5 meters. Computations of internal consistency measures, from a global network of 20 tracking stations, led to an accuracy assessment for those orbits of 1 to 3 meters. Another paper by Fu details the development of a Doppler network in the Peoples Republic of China in which Transit ephemerides and tracking station coordinates were simultaneously adjusted.

For GPS satellites, orbits are routinely computed by the Naval Surface Weapons Center using global data from Air Force and Defense Mapping Agency tracking stations. These multiple-day ephemerides have been used to support GPS operational development and GPS geodetic receiver evaluations.

An alternate approach is the regional network, subject of several presentations. The paper by Wu discussed dual frequency carrier phase observations from the Spring 1985 High Precision Baseline Test to investigate regional orbit determination for GPS satellites. Although ten sites participated in data collection for baseline testing, only carrier phase observations from Air Force Geophysical Laboratory (AFGL) receivers located at the (fiducial) Polaris VLBI sites in Fort Davis, Richmond, and Westford were used to determine (five day) orbits. Resulting orbits were estimated to have an accuracy of better than 10 meters relative to fiducial stations. The objective of this work at the Jet Propulsion Laboratory (JPL) is to develop and demonstrate a capability to dynamically position a lower

altitude satellite such as TOPEX equipped with an on-board GPS receiver. Simulations of such positioning by Wu, using pseudorange observations processed in a difference mode, indicate accuracies approaching 1 meter relative to a fiducial network. Analysis of GPSPAC data from Landsat-5 is planned.

Continuing with this concept Beutler discussed the Bernese GPS software and orbit determination results from the Spring 1985 High Precision Baseline Test. Although prèliminary (full data modeling and use of all observing sites could not be accomplished), the results using double differenced phase observations indicated satellite position accuracies within 0.1 ppm. This ascertion of accuracy followed from the comparison of estimated orbits of differing lengths (internal consistency of orbit determinations) and from comparison of estimated (non-fiducial) station coordinates. Similar analysis presented by Abbot and Abusali concluded orbit accuracies of 0.1 - 0.2 ppm. Such networks are being designed to support geodetic densification as discussed in Landau.

## 5. RECEIVER TECHNOLOGY

The types of GPS receivers designed to support the geodetic community have increased considerably since the early 1980's. A table summarizing commercially available receivers, applicable to geodetic survey, can be found in Archinal and Mueller (1986).

During the session on receiver technology, papers were presented by manufacturers' representatives (and independent investigators) on most commercially available "geodetic" receiver systems, their specifications

and operational characteristics, error budgets, and demonstrated performance against controlled baselines. Several of these systems were available for demonstration.

The papers by Chamberlain of Magnavox and Frei of Wild Heerbrugg described details of the WM 101 GPS satellite surveying equipment and the PoPS post processing software to reduce WM 101 observations from up to a ten station network on an IBM personal computer AT, XT, or equivalent. The former paper discussed the WM 101 design, physical characteristics, operations, and accuracy considerations. Frei discussed the design of the post-processing software and provided some indications of overall WM 101/PoPS performance against an EDM calibration range. For baselines ranging to 1.0 kilometer, test results were within the specifications of 10 mm plus 2 ppm. A second ($L_2$) frequency capability is being planned for the WM 101.

Three papers from Aero Services Division of Western Geophysical Company of America discussed MACROMETER technology. The paper by Cain summarized the performance of the single ($L_1$) frequency MACROMETER V-1000 on some 20 worldwide survey projects. Against independent control the V-1000 model has been verified to 1-2 ppm under Federal Geodetic Control Committee (FGCC) tests. The paper by Welshe summarized the MACROMETER II dual frequency receiver and AIMS software, designed to provide horizontal precision of 1-2 ppm in a 15-30 minute observing session. Receiver packaging has been modified to allow for greater portability. A final paper by Ladd discussed the MINI-MAC survey system under joint development by Aero Services and Litton Aero Products. The system consists of at least two LGS-200 single ($L_1$) frequency C/A code card sets developed by Litton, expandable to dual-band using Aero Services' $L_2$ codeless card (L2CC). Data

will be processed using AIMS software configured on an IBM PC. The LGS-200 units provide C/A pseudorange and $L_1$ carrier phase. Thus receiver synchronization can be achieved for geographically separated units. The LGS-200 also provides a navigation mode. Initial testing of the configuration on a 3 meter baseline demonstrated 1-2 mm consistency with the V-1000.

The Texas Instruments TI-4100 geodetic receiver has undergone extensive performance tests at the Applied Research Laboratories of The University of Texas at Austin. The paper by Coco presented results for satellite signal acquisition rates, noise levels, effect of internal receiver temperature on phase drift, and loss of lock.

In other papers Ashjaee provided a summary of several performance characteristics of the Trimble Model 4000S GPS single ($L_1$) frequency C/A code receiver and Collins discussed the FGCC test of five 4000S units. Specific accuracies achieved during those tests were not provided. Scott proposed a standardized GPS data exchange format designed to be independent of receiver type and computer systems generating or receiving data tapes.

Finally, as a note to owners of older Transit Doppler receivers, Quek and Langley at the University of New Brunswick have interfaced an Apple II to a Canadian Marconi CMA-722B. This greatly extends the tracking capabilities and operational flexibility of that receiver.

## 6. THEORY AND TECHNIQUES FOR GEODETIC POSITIONING

All papers presented on these topics addressed GPS and could be organized into either data modeling or data processing. Those in the former group can be associated with terms found in the following GPS observation equation as pointed out by Wells in his session summary:

The observation equation relates the GPS observed quantity to satellite coordinates, antenna coordinates, clock biases, propagation errors, cycle ambiguity (for phase), and to unmodeled terms.

The paper by Clynch adressed the question of how well one could recover from cycle slips by using simple polynomials to model the change in range due to satellite motion and to phase error introduced by imperfect clocks. Using data from the Spring 1985 High Precision Baseline Test, it was shown that at least a third-order polynomial is required to model raw phase, whereas a second-order polynomial models data from which orbital dynamics have been removed. Using observations over a 20-minute period, double differenced carrier phase can be predicted to within one-half cycle (that is, recovery from loss of phase lock is possible) for up to 3 minutes using crystal oscillators, 6.5 minutes using rubidium clocks, and 9 minutes using a hydrogen maser.

The papers by Tranquilla and Evans both addressed the question of how the effective measurement point on a GPS antenna might vary in the presence of other nearby objects which can influence the electrical characteristics of the antenna. Tranquilla distinguished between **multipath** and **imaging** (electrical coupling between the antenna and nearby structures), described methods of defining and measuring antenna phase center, and described some

examples of GPS antenna design. Evans demonstrated that the effect of multipath on carrier phase is only a few centimeters, while on P code pseudoranges it can be as great as 10 meters; that pseudorange minus Doppler biased range is a good measure of multipath; that at sites having significant multipath, the effect for a specific satellite is very repeatable from day to day; and that each site used in the Spring 1985 High Precision Baseline Test can be characterized by a "multipath coefficient". These coefficients ranged from near zero to 0.6 for the sites with highest multipath. At high multipath sites this effect was large enough to cause receiver loss of lock.

The papers by Kaniuth and Reichert both deal with the problem of estimating tropospheric effects on GPS signals. Kaniuth described a procedure used to derive a local model for a single tracking station, based on three years of radiosonde data from an adjacent weather station. The tropospheric delay predicted by his model using surface weather measurements, agreed very well with that derived from radiosonde data. Reichert's paper described a water vapor radiometer constructed at the University of Bonn.

On the subject of ionospheric refraction Prilepin suggested the use of both carrier and modulation (code) measurements in determining ionospheric refraction corrections. The paper by Campbell addressed the use of Transit Doppler dual-frequency ionospheric corrections to support correction of single-frequency observations from GPS or VLBI. Work on testing this technique is continuing.

The paper by Hilla presented a two-step procedure for detecting and eliminating cycle slips. Large slips (more than 15 cycles) are detected and eliminated using nondifferenced data and taking second differences with respect to time. Smaller slips are then detected and eliminated by

examination of the double difference residual time series. For 18 data sets from the Eifel network, the cycle slips detected with this method generally agreed with cycle slips detected by another investigator (Bock).

A final paper by Mertikas described the problems involving accuracy measures which depend on a Gaussian assumption and pointed out some non-Gaussian characteristics of GPS data.

In the area of data processing Ashkenazi compared different methods for processing phase measurements, directly, or as single, double, or triple differences. Test cases considered baselines varying in length to 58 kilometers. They conclude, that with consistent modeling and appropriate correlation in the weight matrix, processing of phase directly or as a single or double difference should yield equivalent results, as expected. Neglect of the correlation structure for double differences can lead to significantly different parameter estimates. Triple differences with proper correlations, according to Ashkenazi, demonstrated strong dependence on the choice of time interval between successive epochs and produced, in some cases, results showing greater variation. Results based on $L_1$, $L_2$, and $L_1$ and $L_2$ are provided with conclusions on the effects of both ionospheric and tropospheric refraction.

Similar work done by Wei, analyzing data from the 1983 FGCC test of the MACROMETER V-1000, shows consistency between differencing modes to be generally within 0.5 ppm. However, due to data editing differences, exact data sets were not utilized in each case. Emphasis is again placed by Wei on representing proper correlations among double or triple difference observations. Theorems providing a theoretical basis for the equivalence of estimates with or without bias elimination by differencing techniques can be found in the paper by Grafarend. The paper by Wells additionally

addresses this area. Finally, papers by Wu, Kass, Eren, and Delikaraoglou provided modeling and design details associated with various software for GPS positioning.

## 7. TRANSIT APPLICATIONS AND RESULTS

Although the testing and application of GPS have expanded greatly in recent years, major applications of Transit Doppler are continuing. Several significant projects were discussed during the symposium. Wei described a national zero-order control network of 37 points that has been established in the Peoples Republic of China with 1 ppm accuracies over distances exceeding 500 kilometers. In Japan, Doppler control has been used to connect some 13 remote islands to the Japanese Geodetic Coordinate System, to measure distortions in that system (reaching 16 meters at the main island extremes) and for controlling the astrogeodetic geoid. The establishment of a precise geoid in Scandinavia using a network of satellite positions along leveling profiles was discussed by Anderson. Macoco described the use of Transit to delineate ranch boundaries in Kenya.

Regarding tests and analysis associated with Doppler data, Kelm examines the use of various satellite observations for strengthening the readjustment of the European Geodetic Network and concludes that Transit point positions will significantly contribute to the integrity of the network for baselines longer than 500 kilometers. In addition, Kouba demonstrated that processing Doppler data with a multi-station reduction technique, such as found in GEODOP V, may yield precisions of better than 1 ppm for baselines as short as 100 km with sufficient time on site.

In other papers Knopp has found that variations in precise point positions estimated using three main software programs under the African Doppler Survey project produce differences averaging from -0.24 to .21 meters in latitude, from -0.67 to 1.23 meters in longitude, and -1.68 to .15 meters in height. The differences are attributed to preprocessing, weather parameters, and modeling differences among others. Paquet, examining positioning and polar motion results from NOVA, concludes that the continuation of point positioning from a combination of NOVA and OSCAR observations remains acceptable. However, for relative positioning and polar motion, the contribution of OSCAR satellites is no longer useful. With an enhanced gravity model for NOVA, overall Doppler results can be expected to improve further.

## 8. GEODETIC POSITIONING WITH GPS

During 1984 and 1985 a significant number of controlled tests were performed to evaluate the geodetic accuracy of GPS. The analysis of those observations was accomplished using several approaches. Table 1 provides a summary of selected experiments that were reported in Austin.

With regard to tests performed in Hanover, Germany, Wubbena discussed the comparison of a three dimensional network established using TI 4100 GPS receivers with control from precise terrestrial methods including short range laser distance measuring systems. Station misclosure vectors computed from GPS range and phase had components varying from 0.1 to 3.4 centimeters. Baseline length differences, GPS minus laser, ranged from 0.4 to 2.6 centimeters. Site occupation times ranged from 3 to 32 minutes for these 2 to 20 kilometer lines.

In Switzerland during 1985 a local network was established using three types of GPS receivers. The purpose of the activity was to compare results from different receivers, study atmospheric influences, and compare GPS with high precision terrestrial data. As explained by Beutler, the 5 by 6 kilometer network with altitude variations of 900 meters was atypical of many previous GPS test sites because of extreme terrain variations and atmospheric effects. RMS differences between terrestrial derived coordinates and Helmert transformed GPS coordinates were 0.8, 1.5, and 1.0 centimeters for solutions using the V-1000, TR5S, and TI 4100 receivers respectively. Additional details on this experiment are found in Rothacher.

Several papers addressed results from data collected during the Spring 1985 High Precision Baseline Test. The paper by Davidson discussed processing of data acquired at Polaris sites and at the Mojave and Owens Valley VLBI sites in California. Processing AFGL and Series-X phase data in a fiducial mode produced GPS baselines to "new" sites consistent to 0.13 ppm with VLBI determinations. Ware, using GPS orbits, estimated by either MIT or JPL, processed TI-4100 phase data to determine the Owens Valley-Mojave baseline using data acquired over 4 days. GPS results were again consistent with previously derived VLBI results to 1 to 4 parts in $10^7$. Langley, analyzing several baselines in these tests found consistencies with VLBI of 0.5 to 1.8 ppm using the broadcast GPS ephemeris.

In another experiment, Lachapelle solved for baselines of two triangles in western Canada with distances ranging from 10 to 500 km. Computations supported only by the broadcast ephemeris were performed on $L_1$ and $L_2$ alone and on $L_1$ and $L_2$. The results indicate that short baselines can be recovered from 0.5 to 2.0 parts per million using either single or

dual frequency phase. However, the use of dual frequency becomes increasingly important as the baselines lengthen due to greater variability in ionospheric effects. Dual frequency results for baselines in the range of 300 to 500 kilometers were estimated by Lachapelle to be accurate to 1 ppm or better. It is interesting to note that these results appeared to be independent of the receiver clock type.

Finally, in an important paper by Soler, comparisons are made for baselines ranging from 100 to 200 meters and from 10 to 100 kilometers. Observed by both the MACROMETER V-1000 and TI-4100 receivers, data reductions were performed using different options for receiver type, ephemerides, observation span, and processing software (PHASER, SLSQ, MAGNET, INTERF/LSQ). Results for medium length lines (10-30 km), independent of the instrumentation and software, were always better than 3 ppm and in many cases exceeded 1 ppm when compared to precise terrestrial (TCT) control. These results also indicate scale and orientation biases between TCT and GPS. For longer baselines, positioning results exceeded 2 ppm. For extremely short lines results were comparable to those obtained with modern EDM instruments. Azimuths for short lines determined from GPS also demonstrate their potential application in surveying operations.

## 9. DYNAMIC POSITIONING IN SUPPORT OF GEODETIC AND GEOPHYSICAL APPLICATIONS

Kinematic positioning of a survey platform in support of geodetic or geophysical applications may be accomplished using GPS to varying accuracy. The nature of the survey will naturally define the positional requirements for such applications as gravity vector mapping, hydrographic survey, and aerotriangulation, among others. Low accuracy applications typically require 20 to 30 meters and can be achieved using direct positioning with

P-code ranging. Medium accuracy, supporting hydrographic or airboine bathymetric survey, may require 5 to 10 meter accuracy achievable using dynamic relative positioning with P code pseudorange measurements. To achieve accuracies on the order of 0.5 to 2 meters, or better, it will be necessary to process dual frequency range and phase or phase alone. The particular application will also differentiate between the need to recover the platform's trajectory and the need to recover intermittent (static) positions along a survey track. As pointed out by Remondi the consequence may be the requirement (or lack of a requirement) to model receiver processes while traveling between points of interest. Also, depending on the dynamic range of platform motion, receiver loss of lock may be a serious problem to accurately reconstructing the track. Finally, for dynamic relative positioning, the accuracy to which the initial position vector of the platform is known may be a limiting factor in recovering the subsequent platform trajectory. Thus, the particular purpose of the survey will, in general, be the basis for data acquisition, modeling, and reduction requirements.

In this final session of the symposium several authors discussed test results for positioning platforms using GPS observables under different dynamic conditions. Table 2 provides a summary of six of those tests during 1984 and 1985. All experiments used the TI-4100 GPS receiver. In each test, statically located TI-4100 receivers simultaneously tracked in a common four satellite mode. The maximum distance of the platform from a static receiver and the dynamic range in platform velocity are indicated in the table. Maximum platform accelerations, exceeding levels expected in survey applications, may be found for some tests in the proceedings. As expected the observables and rates at which they were acquired, the

modeling of the data, and the method used to process the observations, varied significantly for each test, as did the external standards of comparison used to evaluate the accuracy of the results.

In the experiment described by Cannon, a land vehicle operated at speeds of 45-50 km/hr and speeds to 135 km/hr. Range and phase observations were acquired at rates of 1.2 or 3 seconds depending on vehicle dynamics. Pseudorange observations from a common satellite were processed as difference in range between static and platform receivers; common phase observations were differenced between receivers and differenced again over time forming a change in single differenced phase. Interpolated GPS derived coordinates over the platform path were compared with positions produced from a Ferranti Inertial Surveyor whose accuracy is 0.3 to 0.8 meters. Range only solutions produced RMS agreement with inertially derived horizontal and vertical control to 6 and 7 meters respectively. When phase observables were included results compared at the 2-meter level. Because of interpolation errors (time synchronization between GPS and the inertial surveyor) and the accuracy of the check points, Cannon concluded that the GPS survey may approach an accuracy of 0.5 meters for this application.

The paper by Remondi provides an indication of the accuracy ultimately achievable in (low) dynamic positioning with GPS. The problem of rapidly establishing an extremely accurate initial survey position vector and the determination of subsequent positions is addressed. Using an antenna interchange procedure Remondi demonstrated than an initial survey position, relative to known control, can be rapidly established to less than a centimeter (1-2 mm). Using subsequent phase observations, points along the

platform's path were established to an accuracy of 1 centimeter horizontal by and 2.5 centimeters vertically. This level of accuracy can be achieved in rapid fashion in that only seconds at a point are required.

In conclusion, the capability to establish accurate positions for a moving survey platform has been demonstrated under quite varying conditions. The accuracy achievable will depend on the observables acquired, the dynamic range of the platform, corresponding receiver performance, and on data modeling and processing procedures. The accuracy expected will vary from several centimeters to that provided by the PPS or SPS navigation services.

## 10. FINAL REMARKS

The preceeding sections, covering major symposium sessions, summarize only a limited amount of the information presented during the week. The interested reader should consult the proceedings available from:

Applied Research Laboratories
The University of Texas at Austin
P.O. Box 8029
Austin, Texas 78713-8029

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TABLE 1

GPS POSITIONING RESULTS

| Author | Application | Hardware (Software) | Observable | Data Span | Accuracy | Comparison Standard |
|---|---|---|---|---|---|---|
| Wubbena | 3D Network Baselines 2-20km | TI-4100 (TIPOSIT) | Range & Phase | 3-32 min | 0.4 - 2.6 cm | Precise Control Network |
| Rothacher | 3D Network 5 x 6 km 900m ht variation | V-1000 | Phase | 2 hr | 0.8 cm RMS (2) | Precise Control Network (10 mm) |
| | | TI-4100 | Range & Phase | | 1.5 cm RMS | |
| | | TR5S (BERNESE) | Range & Phase | | 1.0 cm RMS | |
| Davidson | Spring 1985 High Precision Baseline Test (Limited) | AFGL | Phase | Variable | 0.13 ppm(1) | VLBI |
| | | Series-X (GIPSY) | Phase | | | |
| Ware | Spring 1985 High Precision Baseline Test (Limited) | TI-4100 | Phase | Sessions over 4 days | 0.1 - 0.4 ppm(2) | VLBI |
| Langley | Spring 1985 High Precision Baseline Test | TI-4100 (DIPOP) | Phase | 8-16 hr | 0.5 - 1.8 ppm(3) | VLBI |
| Lachapelle | Baselines 10 - 30 km | TI-4100 (Phaser) | Phase $L_1$ or $L_2$ | 4 hr | 0.5 - 2 ppm(3) | -- |
| | 300 - 500 km | | Phase $L_1 + L_2$ | | 1 ppm | |
| Gouldman | Point Positioning 8 sites | TI-4100 | Range | 1 day | Precision (2) 1 - 2 m | -- |

Data reduction incorporates (1) Fiducial approach (2) Precise orbit (3) Broadcast orbit

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| | 300 - 500 km | | Phase $L_1 + L_2$ | | 1 ppm | |
| Souldman | Point Positioning 8 sites | TI-4100 | Range | 1 day | Precision (2) 1 - 2 m | -- |

Data reduction incorporates (1) Fiducial approach (2) Precise orbit (3) Broadcast orbit

## TABLE 2

## GPS DYNAMIC RELATIVE POSITIONING

| Author | Kinematic Test | Dynamic Range | | Receiver System | Observable (rate) | Processing Mode | Accuracy Estimates horizontal/vertical | Comparison Standard (Accuracy) |
|---|---|---|---|---|---|---|---|---|
| | | Max. Distance | Max. Velocity | | | | | |
| Remondi | Land August 1985 | 1 km | 25 km/hr | TI-4100 | Phase (5 sec) | Triple Differences | 1/2.5 cm | Survey Control (several millimeters) |
| Cannon | Land June 1985 | 50 km | 50 km/hr<br>135 km/hr | TI-4100 | Range<br>Range & Phase (1.2 - 3 sec) | Single Differences | 6/7 m<br>2/2 m | Ferranti Inertial Surveyor (0.3 - 0.8 m) |
| Seeber | Sea July 1985 | 1 km | 15 km/hr | TI-4100 | Phase | Range Change | 2/1 m | Polarfix (.1 m + 20 ppm) |
| Kleusberg | Land Spring 1985 | 100 km | 50 km/hr | TI-4100 | Range & Phase | | 1/- m | Horizontal Survey Control |
| Maden | Aircraft July 1985 | 15 km<br>150 m vertical | 400 km/hr | TI-4100 | Range & Phase (3 sec) | Double Differences | -/15 cm | Laser Altimeter |
| Evans | Vertical Motion November 1984 | 24 m<br>3 m vertical | .02 km/hr | TI-4100 | Range & Phase (6 sec) | Double Differences | 6/6 cm | Survey Control Vertical Motion Calibration |

END

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